incorporated into the release computer codes and final User's Manual. Algorithms included in these evaluations are those describing the dynamics of phytoplankton, zooplankton, benthos, fish, sediment, macrophytes, dissolved nutrients, and dissolved organic matter.

The final area of research activity being completed involves the incorporation of several hydraulic features developed under other EWQOS projects (mainly IA and IIIA) into CE-QUAL-R1 and CE-THERM-R1. These hydraulic features include algorithms describing pumped-storage mixing processes, reservoir behavior when ice cover is present, reaeration of project releases through hydraulic structures, inflow mixing processes, and selective withdrawal characteristics for a broader range of structural configurations.

REFERENCES

Collins, C. D., and Wlosinski, J. H. 1983. "Coefficients for Use in the US Army Corps of Engineers Reservoir Model, CE-QUAL-R1," Technical Report E-83-15, Environmental Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Environmental Laboratory. 1982. "CE-QUAL-R1: A Numerical One-Dimensional Model of Reservoir Water Quality; User's Manual," Instruction Report E-82-1 (Revised Edition), US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wlosinski, J. H., et al. 1984. "Evaluation of CE-QUAL-R1: A One-Dimensional Model of Reservoir Water Quality," Technical Report (in preparation), Environmental Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Zimmerman, M. J. 1984. "Initial Evaluation of Computer Algorithms for Simulating Anaerobic Conditions in Reservoirs," Technical Report (in preparation), Environmental Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

TWO-DIMENSIONAL RESERVOIR MODEL

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In nearly all Corps reservoirs, significant gradients in water quality conditions occur along both longitudinal and vertical axes. Understanding how project design and operation influence and are influenced by such gradients may be critical to a given water quality study.

For example, longitudinal variations in reservoir trophic state may be diminished or enhanced by the amount and schedule of project releases. Because of the presence of these gradients in trophic state, anoxic conditions may develop in the upper regions of many reservoirs, in the vicinity of the plunge point rather than in the deep pool, and be advected into the main body of water at metalimnetic depths. Algal blooms may frequently occur in the zone of transition between riverine and lacustrine zones (Thornton et al. 1981), once inflowing solids have settled but while nutrient concentrations are still moderately high. Of special importance to the understanding and analysis of longitudinal gradients is the occurrence of density currents, which may have major impacts on in-pool water quality and thus on project operation. All of these factors contributing to commonly observed longitudinal gradients may complicate the siting of project features such as recreational areas and water intakes. The ability to analyze any of these types of water quality patterns or problems would necessitate a 2-D model.

Although a 2-D model allows for more realistic simulation of reservoir water quality, including an analysis of the representative problems listed above, it must be remembered that a 2-D model is somewhat more costly and difficult to use, calibrate, and interpret, and requires some additional morphometric and field verification data. Thus, if a specific analysis does not require detailed consideration of longitudinal changes in reservoir water quality, a 1-D model will probably suffice and should be employed.

Development of a 2-D water quality model for reservoirs, CE-QUAL-R2, is being conducted in EWQOS Tasks IA.4 and IC.2. This article summarizes progress in model development and evaluation.

DEVELOPMENT OF CE-QUAL-R2

Development of CE-QUAL-R2 has involved cooperative efforts between the WES Hydraulics Laboratory (HL) under EWQOS Task IA.4 and the Environmental Laboratory (EL) under EWQOS Task IC.2. Activities associated with the evaluation of existing multidimensional reservoir hydrodynamic models and with the selection and improvement of a model to serve as the basis of a multidimensional water quality model have taken place in the HL. The EL activities have involved the development and coding of water quality model algorithms to be added to the chosen hydrodynamic code, together with the application and evaluation of the resulting water quality model. Major steps in model development are summarized in Figure 1.

Efforts began with the evaluation of two- and three-dimensional (3-D) hydrodynamic models, including application of promising models to the HL Generalized Reservoir Hydrodynamic (GRH) flume (Johnson 1981, Information Exchange Bulletins E-79-3 and E-80-3). These evaluations showed that 3-D simulations of reservoir hydrodynamics over extended time periods would not be economically practical for some time. Thus, development of a multidimensional water quality model was focused on the 2-D case.

Among the 2-D models considered, the Laterally Averaged Reservoir Model (LARM) developed for the Ohio River Division (Edinger and Buchak 1975, 1979; Buchak and Edinger 1979) was selected as the most promising for future development. LARM1 was felt to possess several desirable features with respect to the development of a water quality model useful for reservoir management and planning. It is a computationally efficient, relatively accurate and stable, unsteady, free-surface model that handles variable density effects on the flow field. By solving surface elevation implicitly this model removes the restrictive Courant stability criterion, permitting the use of longer time steps and the simulation of reasonable time periods for field application (e.g., storm-flow periods, entire stratification cycles).

Following its initial selection two major improvements were made to LARM1: addition of the ability to add and delete upstream computational segments for flooding and drawdown sequences and the development of a transport module for water quality constituents (with the user required to supply appropriate source and sink kinetics). This version of the model is referred to as LARM2 and is documented in Buchak and Edinger (1982b) and Edinger and Buchak (1983a). Subsequently,

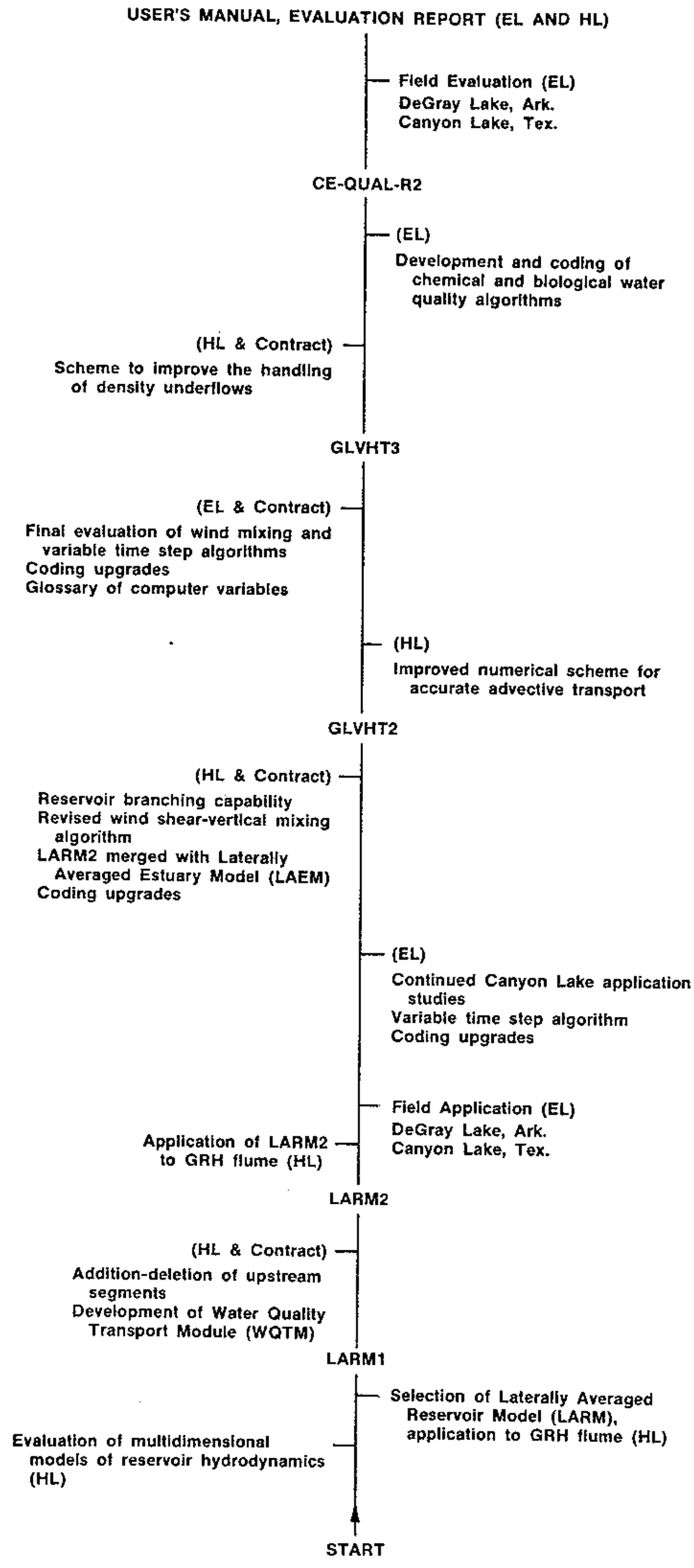


Figure 1. Diagram of the sequence of steps followed in the development of the 2-D water quality model, CE-QUAL-R2. HL refers to activities carried out in the Hydraulics Laboratory under EWQOS Task IA.4; EL refers to activities carried out in the Environmental Laboratory under EWQOS Task IC.2

LARM2 was evaluated more extensively in GRH flume tests against various density-flow cases. These results were discussed in Information Exchange Bulletin E-82-6.

At this point, the ability of the LARM2 code, including the Water Quality Transport Module (WQTM), to simulate field conditions was evaluated using data collected at two CE projects, DeGray Lake, Arkansas, and Canyon Lake, Texas. Results of the DeGray Lake application were presented in Johnson et al. (1981) and Information Exchange Bulletin E-82-6; a portion of the Canyon Lake results are summarized below. The initial field applications and the GRH tests revealed areas where model improvements were needed and provided an enhanced understanding of proper specification of boundary and initial conditions for accurate and stable 2-D simulations. They also demonstrated LARM2's ability to predict the vertical placement of inflows in a stratified pool as well as the transit times and dilution of select water quality constituents. Several enhancements to model output capabilities were made during these studies.

Continuing Canyon Lake model application studies have resulted in several important model improvements. A variable time step algorithm, in which the computational time step is calculated dynamically, was developed, leading to significant reductions in computer costs for model application over extended time periods. Several improvements to the computer code were made, resulting in greater model efficiency and reduced core storage requirements. Also, these studies demonstrated the need for revisions in the way in which wind shear and vertical mixing were handled by the model.

Under an HL contract, revisions were made to provide a more accurate description of wind shear-vertical mixing and to provide the ability to simulate various types of complex branching reservoir geometries. Also, the LARM2 code was merged with a derivative code, the Laterally Averaged Estuarine Model (LAEM) (Edinger and Buchak 1981; Buchak and Edinger 1982a). The resulting code, termed the Generalized Longitudinal-Vertical Hydrodynamics and Transport Model (GLVHT), is a very general code that provides an excellent basis for a water quality model having broad applicability. A number of coding upgrades were associated with these model improvements (Edinger and Buchak 1983b).

Several additional improvements to the code have recently been completed. An improved numerical scheme for accurately computing advective transport was incorporated and evaluated (Dortch and Boyt 1983). The revised wind-mixing and variable time step algorithms were thoroughly evaluated, as was the ability of the code to simulate density underflows. Additional upgrades to the GLVHT2 code have been completed, and a glossary of variables used in this code has been finalized for incorporation in the water quality model User's Manual.

During the time over which the basic hydrodynamic model has undergone development and evaluation, a series of chemical and biological algorithms have been developed for incorporation into the finished GLVHT3 code. These algorithms have been derived from those in the 1-D water quality model CE-QUAL-R1 but modified according to differences between the 1-D and 2-D codes in intended model application and in spatial and temporal scales of model resolution. Incorporation of these water quality algorithms into GLVHT3 to produce CE-QUAL-R2 is being completed with two keys ideas in mind:

- The final water quality model is being coded to allow the user either to simulate reservoir hydrodynamics and water quality conditions simultaneously, or to perform hydrodynamic simulations initially with output files used to drive subsequent water quality simulations.
- Several different levels of complexity are being built into the water quality variables treated by the model, permitting flexibility in model application.

Three different levels or combinations of water quality variables will eventually be included in the model; the user can specify which level he chooses to simulate with an entry in the input data set. The first level of water quality variable definition includes only total dissolved and suspended solids, coliform bacteria, and an arbitrary conservative substance (e.g., dye concentration; temperature is included in the basic hydrodynamic code). Specification of the second level would allow the user to simulate the interactive dynamics of dissolved oxygen-phytoplankton-nutrients (a total of 12 variables in addition to those at the first level). The third level of variable definition (to be added at a later date) will allow further resolution of phytoplankton-nutrient-oxygen dynamics as well as simulation of the release and oxidation of reduced chemical species (e.g., iron, manganese) under aerobic and anaerobic conditions (an additional 11 variables).

Once model development is completed, simulation predictions will be evaluated against extensive data sets already assembled for DeGray and Canyon lakes. Because of the time required to develop CE-QUAL-R2, model evaluation studies under EWQOS will not be as thorough as for CE-QUAL-R1 but will reveal essential information on the advantages, limitations, and appropriate applications of the 2-D model. Once this phase of work has been completed, a User's Manual for CE-QUAL-R2 and a technical paper on model evaluation will be published.

MODEL APPLICATION TO CANYON LAKE, TEXAS

A major test of CE-QUAL-R2 was provided by its application to Canyon Lake, Texas. Canyon Lake (Figure 2) is a deep-storage, multipurpose Corps reservoir located between river km 470 and 488 on the Guadalupe River in Comal County, Texas, approximately 19 km northwest of New Braunfels, Texas. The major purpose of applying a 2-D water quality model to Canyon Lake was to examine effects of density currents on in-pool water quality. Of special interest was the ability to simulate the initial appearance of anoxic conditions in the upper regions of the impoundment in the vicinity of the zone of maximum sedimentation of inflowing solids and nutrients and the subsequent movement of anoxic conditions both upstream and toward the dam over the summer stratification period as influenced by the flow field (Hannan 1979). This application provided a particularly severe test of the basic hydrodynamic portion of CE-QUAL-R2 since Canyon Lake hydrodynamic processes are strongly wind dominated. As a direct result of this application, the 2-D code has undergone significant revision and improvement.

Although the major interest in the Canyon application concerns the spatial and temporal development of anoxic conditions, initial efforts focused on accurate predictions of flow patterns and thermal regimes. Successful completion of this phase of the total effort is critical for two main reasons. First, the ability to produce reasonable simulations of flow fields and thermal regimes indicates that basic hydrodynamic processes are being modeled correctly. Second, since temperature regulates most biological and chemical rate processes, accurate thermal predictions are prerequisite to reliable water quality simulations.

Canyon Lake was divided into computational grid cells of length = 350 m and depth = 1 m; the resulting computational grid had dimensions 49 × 46. Simulations were performed for 1979, with initial conditions being defined for Julian day 106 (i.e., 16 April). Detailed morphometric, hydrometeorological, and tributary flow and temperature data were input to the model as required. Figure 3 depicts typical simulation predictions of temperature profiles for a single near-dam station on two dates and for two stations located at different points along the old river channel on the same date. The degree of agreement between model predictions and observed thermal profiles is generally quite good. Discrepancies between observed and predicted temperatures, especially for surface layers, may be partially attributed to differences in the time during the day at which field temperature measurements were made. These results were substantially improved by the revisions made to the code during these studies.

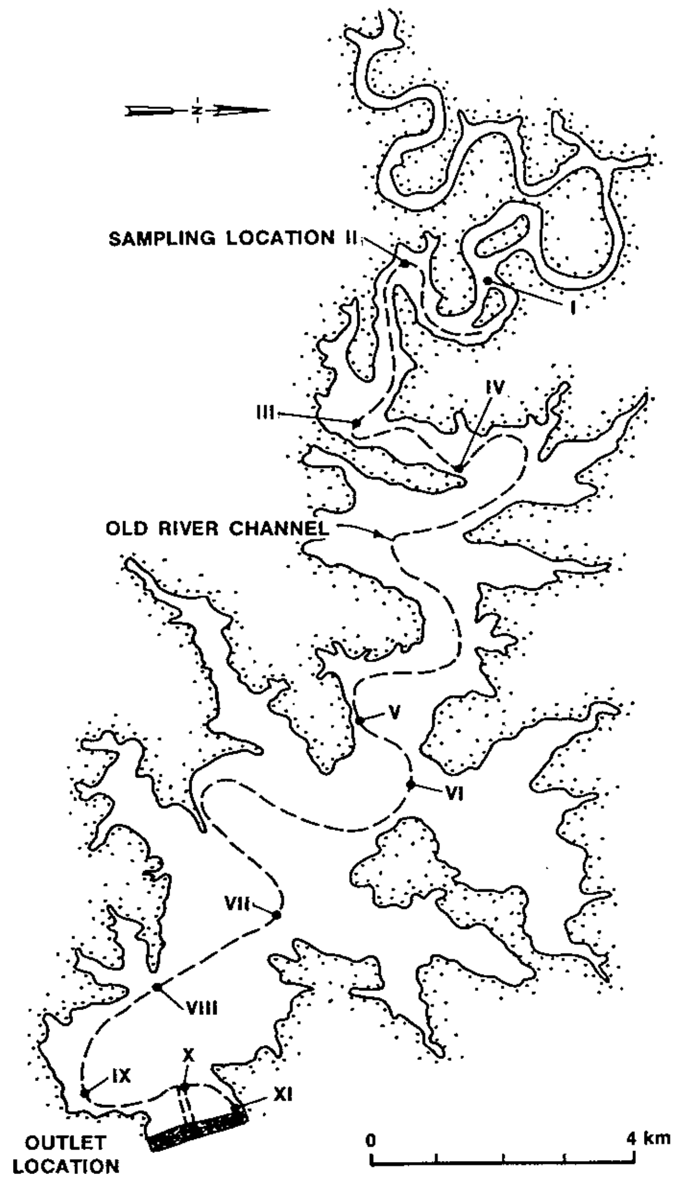
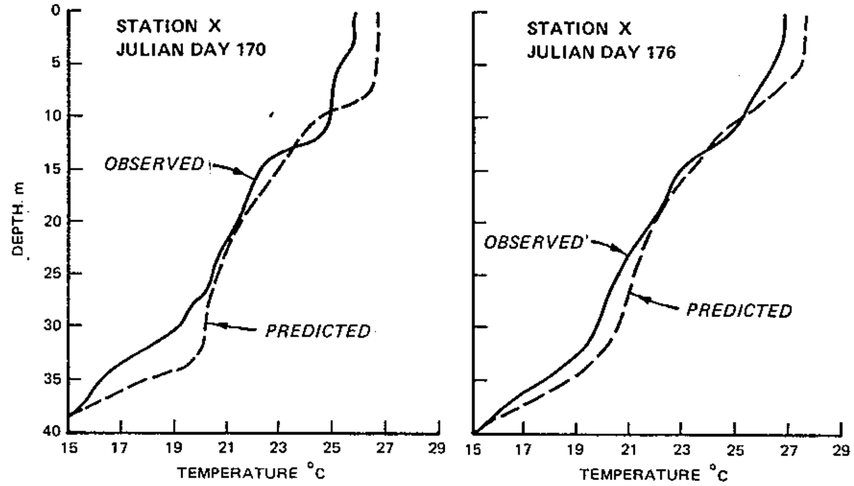
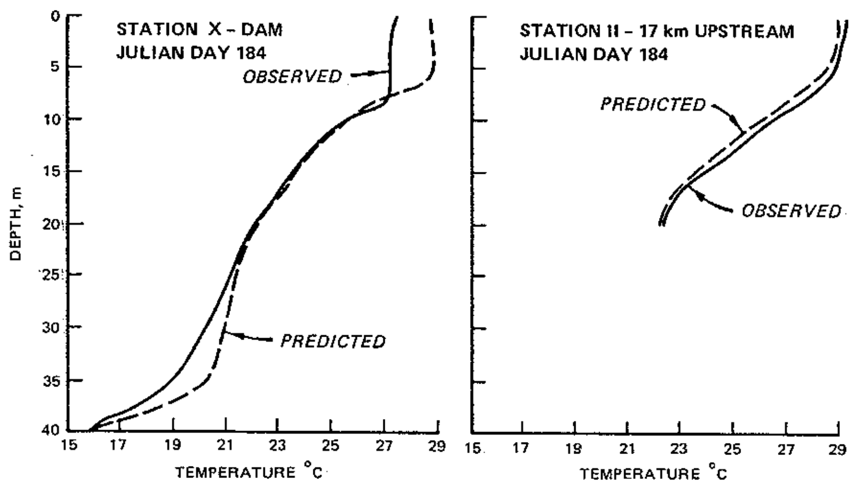


Figure 2. Diagram of Canyon Lake, Texas, showing the location of the old river channel, outlet location, and sampling locations



a. COMPARISON - TWO DAYS, SAME STATION



b. COMPARISON - TWO STATIONS, SAME DAY

Figure 3. Comparison of select observed thermal profiles for Canyon Lake with predicted profiles using a developmental version of CE-QUAL-R2

As previously indicated, Canyon Lake application studies not only provided an important test of the predictive ability of the 2-D model, but also resulted in improvements in model algorithms. Some of these improvements enhanced the model's predictive abilities, while others increased computational efficiency, reduced core storage requirements, and thereby reduced computing costs. For example, for the Canyon Lake application, reductions in core storage requirements resulted in roughly a 22 percent reduction in simulation costs. Enhancements in computational efficiency reduced costs approximately 37 percent. The variable time step algorithm developed during these studies also substantially reduced costs. These cost reductions ranged from about 60 to 85 percent for short- to long-duration simulations (i.e., 1 to 6 months). Although several of these model improvements are still undergoing final evaluation, they have the potential of leading to reductions in 2-D simulation costs and to improvements in model utility.

REFERENCES

Buchak, E. M., and Edinger, J. E. 1979. "A Hydrodynamic, Two-Dimensional Reservoir Model: The User Guide," prepared by J. E. Edinger Associates, Inc., for the US Army Engineer Division, Ohio River, Cincinnati, Ohio.

Buchak, E. M., and Edinger, J. E. 1982a. "User Guide for CE-QUAL-ELV2: A Longitudinal-Vertical, Time-Varying Estuarine Water Quality Model," Instruction Report EL-82-1, prepared by J. E. Edinger Associates, Inc., for the Environmental Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Buchak, E. M., and Edinger, J. E. 1982b. "User Guide for LARM2: A Longitudinal-Vertical, Time-Varying Hydrodynamic Reservoir Model," Instruction Report E-82-3, prepared by J. E. Edinger Associates, Inc., for the Hydraulics Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Dortch, M. S., and Boyt, W. L. 1983. "Simulating Advective Transport in Reservoirs," *Proceedings of the Conference on Frontiers in Hydraulic Engineering*, Hydraulic Division, American Society of Civil Engineers, Cambridge, Mass., pp. 21-26.

Edinger, J. E., and Buchak, E. M. 1975. "A Hydrodynamic, Two-Dimensional Reservoir Model: The Computational Basis," prepared by J. E. Edinger Associates, Inc., for the US Army Engineer Division, Ohio River, Cincinnati, Ohio.

Edinger, J. E., and Buchak, E. M., 1979. "A Hydrodynamic, Two-Dimensional Reservoir Model: Development and Test Application to Sutton Reservoir, Elk River, West Virginia," prepared by J. E. Edinger Associates, Inc., for the US Army Engineer Division, Ohio River, Cincinnati, Ohio.

Edinger, J. E., and Buchak, E. M. 1981. "Estuarine Laterally Averaged Numerical Dynamics: The Development and Testing of Estuarine Boundary Conditions in the LARM Code," Miscellaneous Paper EL-81-9, prepared by J. E. Edinger Associates, Inc., for the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Edinger, J. E., and Buchak, E. M., 1983a. "Developments in LARM2: A Longitudinal-Vertical, Time-Varying Hydrodynamic Reservoir Model," Technical Report E-83-1, prepared by J. E. Edinger Associates, Inc., for the Hydraulics Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Edinger, J. E., and Buchak, E. M. 1983b. "Recent Developments in Numerical, Longitudinal-Vertical Hydrodynamics and Transport," Draft Report, prepared by J. E. Edinger Associates, Inc., for the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Hannan, H. H. 1979. "Chemical Modifications in Reservoir-Regulated Streams," *The Ecology of Regulated Streams*, eds., J. V. Ward and J. A. Stanford, Plenum Publishing Company, New York, pp 75-93.

Johnson, B. H. 1981. "A Review of Numerical Reservoir Hydrodynamic Modeling," Technical Report E-81-2, Hydraulics Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Johnson, M. C., et al. 1981. "Analyzing Storm Event Data from DeGray Lake, Arkansas, Using LARM," presented at the ASCE 1981 Convention and Exposition, St. Louis, Mo.

Thornton, K. W., et al. 1981. "Reservoir Sedimentation and Water Quality — An Heuristic Model," *Proceedings of a Symposium on Surface Water Impoundments*, American Society of Civil Engineers, Minneapolis, Minn., Vol I, pp 654-661.

RESERVOIR MODELING TECHNOLOGY TRANSFER ACTIVITIES

Because of the importance of transferring water quality numerical modeling technologies to the appropriate user communities, major efforts have been devoted to technology transfer activities for both CE-QUAL-R1 and R2.

The most critical aspect of technology transfer within the 1-D modeling area has been the publication, revision, and distribution of the User's Manual for CE-QUAL-R1. To date this manual has been distributed to over 100 potential users who requested copies: Corps District and Division offices, State and other Federal agencies, universities, and private firms. Future revisions of the manual will automatically be mailed to all holders of record.

The central feature of technology transfer for CE-QUAL-R2 will also be a User's Manual, as well as an associated model evaluation paper, both scheduled for later this year.

Two training sessions on the use of CE-QUAL-R1/CE-THERM-R1 have been held: one for Corps personnel and one for the U.S. Bureau of Reclamation (USBR). The Corps' training course (Course No. 191: Water Quality and Ecological Models), held in Vicksburg, Miss., was attended by 14 Corps District and Division personnel and a representative of USBR. A workshop sponsored by USBR Engineering and Research Center (ERC) was held in Denver. This session was attended by 17 personnel of both USBR regional offices and the ERC.

Both the training course and the workshop provided participants with in-depth training in the use and interpretation of the 1-D model and submodel as well as a lecture on the need for and general properties of CE-QUAL-R2. Similar training sessions will be held in the future.

Several other activities have made potential users aware of the existence and properties of both reservoir models. A detailed presentation on CE-QUAL-R1/CE-THERM-R1 and a general presentation on CE-QUAL-R2 were made to the third meeting of the Water Quality and Ecological Modeling Working Group of the Interagency Water Quality and Ecology Committee for Research Coordination. The meeting, hosted by USBR ERC and held in Denver, Colo., was attended by representatives of the USBR, Tennessee Valley Authority, U.S. Environmental Protection Agency, and the Corps. As part of the 15th EWQOS Field Review Group meeting held in the North Pacific Division (NPD) Office in Portland, Oreg., a general briefing on 1- and 2-dimensional reservoir water quality modeling was presented to personnel from NPD and the Portland District. A similar briefing was recently given to personnel of the South Atlantic Division, and a lecture on the current status and properties of CE-QUAL-R1 and R2 was included in the Fifth Corps Water Quality Seminar held recently in Portland (Dortch and Waide 1984).*

* Dortch, M. S., and Waide, J. B. 1984. "Developments in Water Quality Models for Surface Waters," *Proceedings of a Seminar in Water Quality Control* (R. G. Willey, ed.), Committee on Water Quality, U.S. Army Corps of Engineers, Washington, D.C. (in press).

CHANGE OF COMMAND AT WES

Col. Robert C. Lee has been named as the new Commander and Director of the U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, Miss. He succeeds Col. Tilford C. Creel, who is retiring from the U.S. Army in July 1984.

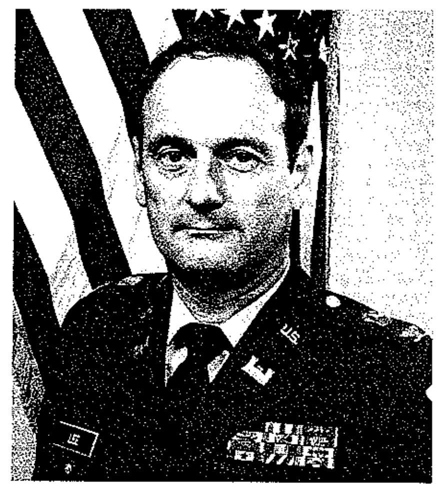
As WES Commander and Director, Lee will oversee the operation of the Corps of Engineers' largest research facility. The WES budget for research and development exceeds $100 million each year.

WES is a five-laboratory complex which employs over 1600 civilian and military personnel. Some of the broad fields of WES research include: hydraulic, coastal, geotechnical, structural, and environmental engineering.

Lee's previous assignment was as the New Orleans District Engineer since August of 1981. As head of the New Orleans District of the Corps of Engineers, Lee was responsible for all flood control and navigation projects in a 30,000 square mile area which included most of south Louisiana.

Col. Creel, who was the 21st WES Commander and Director, is retiring from the U.S. Army after 30 years of service. His previous assignments have included District Engineer, Savannah District of the Corps of Engineers; assistant director of civil works, Upper Mississippi Basin and Great Lakes area, Office of the Chief of Engineers; and legislative liaison duty in the Secretary of the Army's Office in Washington, D.C.

During his years of military service, Creel has held troop assignments in such areas as the Republic of Vietnam, Germany, and Massachusetts.



Col. Robert C. Lee

Col. Tilford C. Creel